

Enhanced $B_s-\bar{B}_s$ lifetime difference and anomalous like-sign dimuon charge asymmetry from new physics in $B_s \rightarrow \tau^+\tau^-$

Amol Dighe,¹ Anirban Kundu,² and Soumitra Nandi³

¹Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India

²Department of Physics, University of Calcutta, 92 Acharya Prafulla Chandra Road, Kolkata 700009, India

³Dipartimento di Fisica Teorica, Univ. di Torino and INFN, Sezione di Torino, I-10125 Torino, Italy

(Dated: July 12, 2010)

New physics models that increase the decay rate of $B_s \rightarrow \tau^+\tau^-$ contribute to the absorptive part of $B_s-\bar{B}_s$ mixing, and may enhance $\Delta\Gamma_s$ all the way up to its current experimental bound. In particular, the model with a scalar leptoquark can lead to a significant violation of the expectation $\Delta\Gamma_s \leq \Delta\Gamma_s^{\text{SM}}$. It can even allow regions in the $\Delta\Gamma_s-\beta_s$ parameter space that are close to the best fit obtained by CDF and DØ through $B_s \rightarrow J/\psi\phi$. In addition, it can help explain the anomalous like-sign dimuon charge asymmetry observed recently by DØ. A measurement of $BR(B_s \rightarrow \tau^+\tau^-)$ is thus crucial for a better understanding of new physics involved in $B_s-\bar{B}_s$ mixing.

PACS numbers: 14.40.Nd, 13.20.He, 13.25.Hw, 12.60.-i

Keywords: B mesons, Lifetime difference, Dimuon asymmetry, Leptoquarks, Physics beyond the Standard Model

I. INTRODUCTION

In the standard model (SM), the Cabbibo-Kobayashi-Maskawa (CKM) mixing matrix is the only source of charge-parity (CP) violation. The data from the decays of K , D and B mesons have so far been consistent with this paradigm, however the flavor changing neutral current (FCNC) processes involving $b \rightarrow s$ transitions are expected to be sensitive to many sources of new physics (NP) [1]. This is why the B_s meson is one of the most important and interesting portals for indirect detection of such NP models.

In this paper we shall concentrate on the oscillation parameters in the $B_s-\bar{B}_s$ system. The average decay width $\bar{\Gamma}_s \equiv (\Gamma_{sH} + \Gamma_{sL})/2 = (0.679^{+0.013}_{-0.011}) \text{ ps}^{-1}$ and the mass difference $\Delta M_s \equiv M_{sH} - M_{sL} = (17.77 \pm 0.10 \pm 0.07) \text{ ps}^{-1}$ have already been measured to an accuracy of better than $\sim 2\%$ [2–4] and play an important role in constraining any new physics. Here the labels L and H stand respectively for the light and heavy mass eigenstates in the neutral B_s system. The decay width difference $\Delta\Gamma_s \equiv \Gamma_{sL} - \Gamma_{sH}$ and the $B_s-\bar{B}_s$ mixing phase are relatively less certain. The SM predictions for these quantities are [5]

$$\Delta\Gamma_s^{\text{SM}} = (0.096 \pm 0.039) \text{ ps}^{-1}, \quad (1)$$

$$\beta_s^{J/\psi\phi(\text{SM})} = \text{Arg}\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \approx 0.019 \pm 0.001, \quad (2)$$

where $2\beta_s^{J/\psi\phi}$ is the mixing phase relevant for $B_s \rightarrow J/\psi\phi$ decay. The recent CDF and DØ measurements [6, 7], using the angular analysis in $B_s \rightarrow J/\psi\phi$ decay [8, 9], give [10]

$$\Delta\Gamma_s = \pm(0.154^{+0.054}_{-0.070}) \text{ ps}^{-1}, \quad (3)$$

$$\beta_s^{J/\psi\phi} = (0.39^{+0.18}_{-0.14}) \cup (1.18^{+0.14}_{-0.18}), \quad (4)$$

where the second set in the last line is just the complement of $\pi/2$ for the first set. This reflects the ambiguity

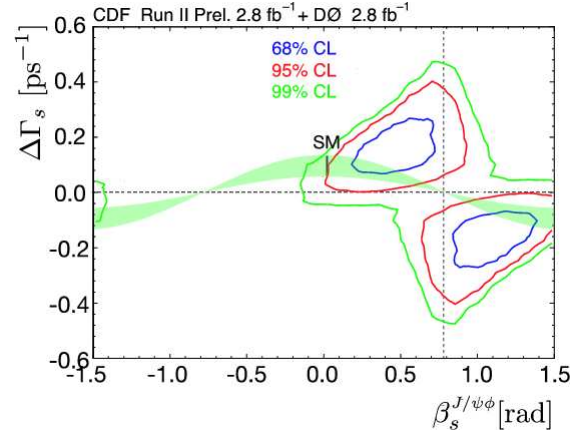


FIG. 1: The combined experimental constraints by CDF and DØ through $B_s \rightarrow J/\psi\phi$. Blue, red and green contours (from inner to outer) correspond to the 68%, 95% and 99% C.L. regions. The sinusoidal green band corresponds to the relation $\Delta\Gamma_s \approx \Delta\Gamma_s^{\text{SM}} \cos \phi_s$, valid when NP does not contribute to Γ_{12s} . The figure is taken from [7].

in the determination of $\beta_s^{J/\psi\phi}$. Note that the sign of $\Delta\Gamma_s$ is undetermined. The positive and negative signs correspond, respectively, to the two disconnected regions in the allowed parameter space for $\beta_s^{J/\psi\phi}$. Alternative ways of removing this sign ambiguity have been suggested in [11]. The correlated constraints are shown in Fig. 1. The SM prediction for $(\Delta\Gamma_s, \beta_s^{J/\psi\phi})$ is excluded by the data to 90% C.L.. Hence the exploration of new physics effects on these quantities becomes imperative.

While many new physics models can affect $\beta_s^{J/\psi\phi}$ and make its value anywhere in its conventional allowed range $[-\pi/2, \pi/2]$, the ability of new physics to influence $\Delta\Gamma_s$ is rather limited. Indeed, the width difference is

$$\Delta\Gamma_s = 2|\Gamma_{12s}| \cos \phi_s, \quad (5)$$

where $\phi_s \equiv \text{Arg}(-M_{12s}/\Gamma_{12s})$. Here M_{12s} and Γ_{12s} are the dispersive and absorptive parts, respectively, of the B_s - \overline{B}_s mixing amplitude. In the SM [5]

$$\phi_s = 0.0041 \pm 0.0007, \quad (6)$$

and hence $\Delta\Gamma_s^{\text{SM}} \approx 2|\Gamma_{12s}|$. The class of NP models which do not affect Γ_{12s} then satisfy $\Delta\Gamma_s \leq \Delta\Gamma_s^{\text{SM}}$ [12]. These include the minimal flavour violating models [13] where the bases in the quark flavor space are the same as that in the SM, as well as models where the mixing box diagram contains only heavy degrees of freedom. The predictions of these models for $(\Delta\Gamma_s, \beta_s^{J/\psi\phi})$ will then be restricted to the sinusoidal band shown in Fig. 1. Note that only a small part of this band is within the 68% C.L. region, so that NP of this type will be unable to account for the measurements if the errors decrease with the best fit values staying unchanged.

However, there are well-motivated models where the B_s - \overline{B}_s mixing box diagram contains two light degrees of freedom, resulting in an absorptive amplitude. Given the current strong constraints on the B_s decays to hadrons, e^+e^- and $\mu^+\mu^-$ [2], the only candidate for the intermediate light particle is τ . In an earlier publication [14], we had implemented this idea with two examples: (i) the model with a scalar leptoquark, and (ii) R-parity violating supersymmetry. These models can have *flavor dependent* couplings of a light particle with a heavy new particle – in particular, τ can couple with the leptoquark or squark – and hence can contribute to Γ_{12s} . A significant enhancement of $\Delta\Gamma_s$ was shown to be possible in the former model [14]. In this paper we shall investigate the effect of the leptoquark on the correlation between $\Delta\Gamma_s$ and $\beta_s^{J/\psi\phi}$, keeping in mind that any such new physics will also significantly affect the decay rate $B_s \rightarrow \tau^+\tau^-$.

Recently, the DØ collaboration has claimed evidence for an anomalous like-sign dimuon charge asymmetry [15]

$$A_{\text{sl}}^b = -0.00957 \pm 0.00251 \pm 0.00146. \quad (7)$$

CDF has also measured the same quantity using 1.6 fb⁻¹ of data and found $A_{\text{sl}}^b = (8.0 \pm 9.0 \pm 6.8) \times 10^{-3}$ [16]. Combining these two, one gets

$$A_{\text{sl}}^b = -(8.5 \pm 2.8) \times 10^{-3}, \quad (8)$$

which differs from the SM prediction

$$A_{\text{sl}}^{b(\text{SM})} = -0.00023_{-0.00006}^{+0.00005} \quad (9)$$

by about 3σ . Such an asymmetry can be used as a probe of the flavor structure of new physics [17]. It turns out that the same new physics that enhances $\Delta\Gamma_s$ can also help in explaining this anomaly. We shall elaborate on this in the latter part of this paper.

II. NEW PHYSICS IN $B_s \rightarrow \tau^+\tau^-$

Leptoquarks (LQ) are color-triplet objects that couple to quarks and leptons. They occur generically in GUTs

[18], composite models [19], and superstring-inspired E_6 models [20]. Model-independent constraints on their properties are available [21], and the prospects of their discovery at the LHC have also been studied [22].

The direct production limits depend on the LQ model, as well as the SM fermions these LQs can couple to. The bounds on the second and third generation leptoquarks are, respectively, $M_{\text{LQ}} > 316, 245$ GeV, when they are pair produced [2, 23]. A third generation scalar leptoquark decaying only into a b -quark and a τ lepton has a mass bound of 210 GeV [24]. We shall conservatively take $M_{\text{LQ}} = 250$ GeV in this analysis. However our results hold even with much higher M_{LQ} , by appropriately scaling the coupling $|h_{\text{LQ}}|$ as shall be seen later.

We shall restrict ourselves to scalar leptoquarks that are singlets under the $\text{SU}(2)_L$ gauge group of the SM. This is because vector or most of the $\text{SU}(2)_L$ nonsinglet leptoquarks tend to couple directly to neutrinos, hence we expect that their couplings are tightly constrained from the neutrino mass and mixing data. This makes any significant effect on the B_s - \overline{B}_s system unlikely.

The relevant interaction term for a scalar $\text{SU}(2)_L$ singlet leptoquark is of the form

$$\mathcal{L}_{\text{LQ}} = \lambda_{ij} \overline{d}_R^c e_{iR} \mathcal{S}_0 + \text{h.c.}, \quad (10)$$

where d_R and e_R stand for the right-handed down-type quarks and right-handed charged leptons, respectively, and i, j are generation indices that run from 1 to 3. The couplings λ_{ij} can in general be complex, and some of them may vanish depending on any flavor symmetries involved. We take the LQ couplings in the quark mass basis. This is the most economical choice given the fact that we do not know the rotation matrix for the right-chiral down-type quark fields. One can also have an $\text{SU}(2)_L$ doublet leptoquark, whose interaction is of the form

$$\mathcal{L}_{\text{LQ}} = \lambda_{ij} \overline{q}_{jL} i\sigma_2 e_{iR} \mathcal{S}_{\frac{1}{2}} + \text{h.c.}, \quad (11)$$

which gives almost identical results.

When λ_{32} and λ_{33} are nonzero, the interaction in eq. (10) generates an effective four-fermion $(S+P) \otimes (S+P)$ interaction leading to $b \rightarrow s\tau^+\tau^-$. This will contribute to B_s - \overline{B}_s mixing (with τ and \mathcal{S}_0 flowing inside the box), to the leptonic decay $B_s \rightarrow \tau^+\tau^-$, and to the semileptonic decays $B \rightarrow X_s\tau^+\tau^-$. The relevant quantity here is the coupling product

$$h_{\text{LQ}}(b \rightarrow s\tau^+\tau^-) \equiv \lambda_{32}^* \lambda_{33}. \quad (12)$$

One may get a tight constraint on $|h_{\text{LQ}}|$ from $B_s \rightarrow \tau^+\tau^-$. One expects the lifetimes of B_d and B_s to be the same in the Standard Model: $\tau_{B_s}/\tau_{B_d} = 1.00 \pm 0.01$ [2]. This is certainly true if we assume spectator dominance: the decays which do not have a spectator quark contribute negligibly in the total decay width. Experimentally, $\Gamma_s/\Gamma_d - 1 = (3.6 \pm 1.8)\%$ [10]. Thus, the branching ratio $\mathcal{B} \equiv \text{BR}(B_s \rightarrow \tau^+\tau^-)$ can be as large as 6–7%. Considering the deviations from the naive spectator model,

which is expected to be small for the B_d - B_s system, one may conservatively put the upper bound for \mathcal{B} at 10%. The value of \mathcal{B} is only $\mathcal{O}(10^{-8})$ in the SM. This decay has not been observed, nor is a direct measurement of an upper bound on its branching ratio available. A similar estimate of $\mathcal{B} \sim 5\%$ is available in [25]. If indeed $|h_{\text{LQ}}|$ is large enough to cause such a significant enhancement in \mathcal{B} , it is related to \mathcal{B} directly through

$$\mathcal{B} \approx \frac{|h_{\text{LQ}}|^2}{128\pi M_{\text{LQ}}^4} \frac{f_{B_s}^2 M_{B_s}^3}{\bar{\Gamma}_s} \frac{m_\tau^2}{M_{B_s}^2} \sqrt{1 - 4 \frac{m_\tau^2}{M_{B_s}^2}} \\ \approx 9.5\% \left(\frac{|h_{\text{LQ}}|}{0.3} \right)^2 \left(\frac{250 \text{ GeV}}{M_{\text{LQ}}} \right)^4 \left(\frac{f_{B_s}}{0.250 \text{ GeV}} \right), \quad (13)$$

where f_{B_s} is the B_s decay constant. It can be seen that for $M_{\text{LQ}} = 250 \text{ GeV}$, $\mathcal{B} \approx 10\%$ can accommodate $|h_{\text{LQ}}| \approx 0.3$.

We shall show in the next sections that the values of $|h_{\text{LQ}}|$ allowed by the above analysis can cause significant changes in the values of $\Delta\Gamma_s$ and $\beta_s^{J/\psi\phi}$, and can also enhance A_{sl}^b by a sizeable amount.

III. NEW PHYSICS IN $\Delta\Gamma_s$ AND $\beta_s^{J/\psi\phi}$

In the presence of NP contribution, the expressions for the dispersive and absorptive parts of B_s - \bar{B}_s mixing can be written as

$$M_{12s} = M_{12s}^{\text{SM}} + M_{12s}^{\text{LQ}} = M_{12s}^{\text{SM}} R_M e^{i\phi_M}, \quad (14)$$

$$\Gamma_{12s} = \Gamma_{12s}^{\text{SM}} + \Gamma_{12s}^{\text{LQ}} = \Gamma_{12s}^{\text{SM}} R_\Gamma e^{i\phi_\Gamma}. \quad (15)$$

The standard model contributions, to leading order (LO) in $1/m_b$ and $\alpha_s(m_b)$, are given by [26, 27]

$$M_{12s}^{\text{SM}} = (V_{tb}V_{ts}^*)^2 \frac{G_F^2}{12\pi^2} \chi_{B_s} \hat{\eta}_{B_s} M_W^2 S_0(x_t), \quad (16)$$

$$\Gamma_{12s}^{\text{SM}} = -[(V_{cb}V_{cs}^*)^2 \Gamma^{cc} + (V_{ub}V_{us}^*)^2 \Gamma^{uu} \\ + 2(V_{cb}V_{cs}^*V_{ub}V_{us}^*) \Gamma^{cu}], \quad (17)$$

where $\chi_{B_s} \equiv M_{B_s} B_{B_s} f_{B_s}^2$, and Γ^{ij} , the absorptive parts of the box diagrams (without the CKM factors) with quarks i and j flowing inside the loop, are given in [5]. The short distance behavior is contained in $\hat{\eta}_{B_s}$, which incorporates the QCD corrections, and in the Inami-Lim function $S_0(x_t)$. The value of Γ_{12s}^{SM} has been calculated up to $\mathcal{O}(1/m_b^2)$ in [28], wherein some NP contributions to $\Delta\Gamma_s$ have also been studied.

The leading order leptoquark contributions to the above quantities are [14]

$$M_{12s}^{\text{LQ}} = \frac{h_{\text{LQ}}^2}{384\pi^2 M_{\text{LQ}}^2} \chi_{B_s} \hat{\eta}_{B_s} \tilde{S}_0(x_\tau), \quad (18)$$

$$\Gamma_{12s}^{\text{LQ}(0)} = -\frac{h_{\text{LQ}}^2}{256\pi M_{\text{LQ}}^4} \chi_{B_s} m_b^2 F(\tau), \quad (19)$$

where $\tilde{S}_0(x_\tau)$ is another Inami-Lim function, and the phase space factor is $F(\tau) = 0.64$. The details of the calculation may be found in [14].

While the next to leading order QCD corrections and the $1/m_b$ corrections do not affect M_{12s}^{SM} significantly, they modify Γ_{12s}^{SM} by $\sim 30\%$ from its LO value [29]. The QCD corrections are expected to be different for SM and LQ operators since the mediating heavy particle for the latter case is a color triplet. The $1/m_b$ corrections are also expected to differ since the light degrees of freedom that flow inside the mixing box are different too. While it is desirable to have an idea of these corrections, since we are only showing typical results from allowed leptoquark parameters, such corrections can be absorbed by just changing the value of M_{LQ} and the phase of h_{LQ} . Therefore in our numerical analysis, we use the SM predictions for Γ_{12s}^{SM} [5] that include the NLO QCD and $1/m_b$ corrections, however for Γ_{12s}^{LQ} we only use the leading order contribution. For the sake of clarity, while calculating the combined SM and LQ contribution to Γ_{12s} , we use only the central value of the SM prediction. Including the 30% error in the SM prediction will widen the bands for our results shown in Fig. 2.

In the presence of leptoquarks, eqs. (5,14,15) lead us to write the width difference as

$$\Delta\Gamma_s = 2|\Gamma_{12s}^{\text{SM}}| R_\Gamma \cos(\phi_M - \phi_\Gamma - 2\beta_s^{\text{SM}}) \\ \approx \Delta\Gamma_s^{\text{SM}} R_\Gamma \cos(\phi_M - \phi_\Gamma), \quad (20)$$

where the approximation uses $\beta_s^{\text{SM}} \approx 0$. The allowed values of h_{LQ} permit $R_\Gamma \cos(\phi_M - \phi_\Gamma) > 1$, so that the value of $\Delta\Gamma_s$ can be enhanced in this model. Fig. 2 shows that the enhancement can be even up to $\Delta\Gamma_s \approx 0.4 \text{ ps}^{-1}$ for $|h_{\text{LQ}}| \approx 0.3$.

The decay $B_s \rightarrow J/\psi\phi$ exhibits CP violation through the interference of mixing and decay. The CP violating phase measured through the time dependent angular distribution of this decay is

$$\beta_s^{J/\psi\phi} \approx \frac{1}{2} \text{Arg} \left(-\frac{(V_{cb}V_{cs}^*)^2}{M_{12s}} \right) = \beta_s^{J/\psi\phi(\text{SM})} - \frac{\phi_M}{2}, \quad (21)$$

where we have used the approximation $|\Gamma_{12s}| \ll |M_{12s}|$. Clearly at low values of $|h_{\text{LQ}}|$, the allowed range of ϕ_M will be restricted to be near zero, and hence $\beta_s^{J/\psi\phi}$ will be close to its SM value, which itself is close to zero. For higher $|h_{\text{LQ}}|$, however, the value of ϕ_M can be anything, and hence $\beta_s^{J/\psi\phi}$ can be anywhere in its conventional range $[-\pi/2, \pi/2]$. This is illustrated in Fig. 2.

Figure 2 overlays our predictions with the leptoquark model in the $\Delta\Gamma_s$ - $\beta_s^{J/\psi\phi}$ plane on the results of the combined analysis of CDF and DØ. Clearly, the additional leptoquark contribution not only can enhance $\Delta\Gamma_s$ and β_s , but also can allow us to be well within the 68% C.L. region of the current best fit.

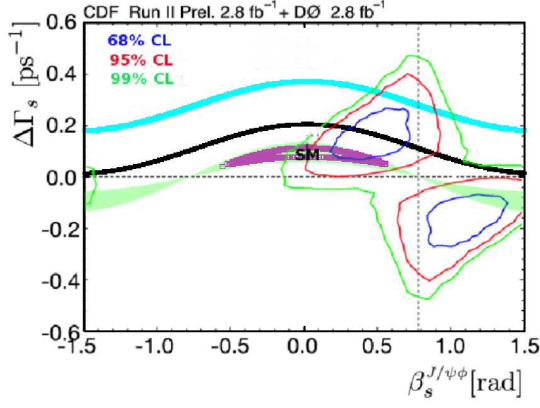


FIG. 2: The predictions of $(\Delta\Gamma_s, \beta_s^{J/\psi\phi})$ within the scalar leptoquark model, overlaid on the combined experimental constraints by CDF and DØ through $B_s \rightarrow J/\psi\phi$ (Fig. 1). Magenta (dark gray), black and aqua (light gray) bands correspond to $|h_{LQ}| = 0.07, 0.17$ and 0.27 , respectively, with $M_{LQ} = 250$ GeV.

IV. NEW PHYSICS IN A_{sl}^b

The like-sign dimuon charge asymmetry A_{sl}^b measured by DØ [15] and CDF [16] is related to the semileptonic decay asymmetries a_{sl}^d and a_{sl}^s in the B_d and B_s sectors, respectively, through [15]

$$A_{sl}^b = (0.506 \pm 0.043) a_{sl}^d + (0.494 \pm 0.043) a_{sl}^s. \quad (22)$$

The coefficients here are valid even in the presence of NP. The average A_{sl}^b from eq. (8), and the current experimental constraints of $a_{sl}^d = -0.0047 \pm 0.0046$ [10], yield

$$a_{sl}^s = -0.012 \pm 0.007, \quad (23)$$

which is almost 2σ away from the SM prediction [5]

$$a_{sl}^{s(\text{SM})} = (2.1 \pm 0.6) \times 10^{-5}. \quad (24)$$

This quantity is directly related to $\Delta\Gamma_s$ and the B_s - \overline{B}_s mixing phase via

$$a_{sl}^s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan \phi_s^{sl} = -\frac{\Delta\Gamma_s}{\Delta M_s} \tan 2\beta_s^{sl}, \quad (25)$$

where $\phi_s^{sl} \equiv \text{Arg}(-M_{12s}/\Gamma_{12s}) = \phi_s$ and we have defined β_s^{sl} such that $\phi_s^{sl} = -2\beta_s^{sl}$. From eq. (6), we have

$$\beta_s^{sl} = -0.0020 \pm 0.0003. \quad (26)$$

In the presence of NP that affects Γ_{12s} , eqs. (14) and (15) yield the relation

$$\beta_s^{sl} = \frac{1}{2} \text{Arg} \left(-\frac{\Gamma_{12s}}{M_{12s}} \right) = \beta_s^{sl(\text{SM})} - \frac{\phi_M}{2} + \frac{\phi_\Gamma}{2}. \quad (27)$$

Since $\beta_s^{J/\psi\phi(\text{SM})} \approx 0 \approx \beta_s^{sl(\text{SM})}$, eqs. (21) and (27) clearly show that β_s^{sl} is in general different from $\beta_s^{J/\psi\phi}$. Note

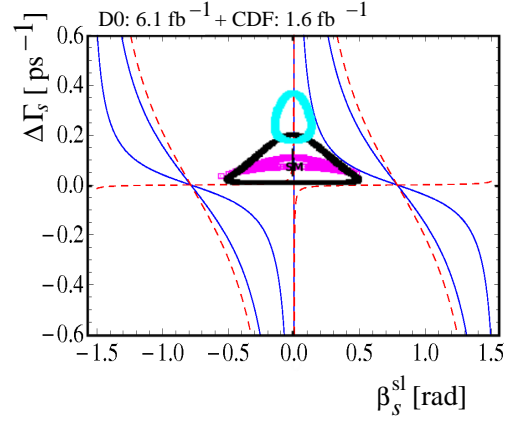


FIG. 3: The predictions for $(\Delta\Gamma_s, \beta_s^{sl})$ within the scalar leptoquark model, overlaid on the 68% (continuous blue) and 95% (dashed red) C.L. contours for the combined DØ and CDF measurements of a_{sl}^s . Magenta (dark gray), black and aqua (light gray) bands correspond to $|h_{LQ}| = 0.07, 0.17$ and 0.27 , respectively, with $M_{LQ} = 250$ GeV.

that when NP does not affect Γ_{12s} , the value of ϕ_Γ vanishes and only then can one say $\beta_s^{sl} \approx \beta_s^{J/\psi\phi}$. Therefore, it is not recommended to superimpose the parameter spaces of $(\Delta\Gamma_s, \beta_s^{sl})$ and $(\Delta\Gamma_s, \beta_s^{J/\psi\phi})$.

In Fig. 3, we show the constraints in the $(\Delta\Gamma_s, \beta_s^{sl})$ parameter space coming from the A_{sl}^b (consequently, a_{sl}^s) measurement in [15], and $(\Delta\Gamma_s, \beta_s^{sl})$ predictions at some allowed $|h_{LQ}|$ values. It shows that the leptoquark contribution can give rise to a_{sl}^s values well within the 95% C.L. region of the experimental data. Note that the predictions shown in Figs. 2 and 3 correspond to the same set of NP parameters. This again illustrates the need to clearly differentiate between β_s^{sl} and $\beta_s^{J/\psi\phi}$.

V. SUMMARY AND CONCLUSIONS

The model with a scalar leptoquark, presented in this paper, belongs to the special class of NP models that affect the absorptive part Γ_{12s} of B_s - \overline{B}_s mixing. It can therefore evade the relation $\Delta\Gamma_s < \Delta\Gamma_s^{SM}$ and can give enhanced values of the lifetime difference in B_s - \overline{B}_s system. The enhancement in $\Delta\Gamma_s$ also corresponds to an enhancement in the branching ratio $BR(B_s \rightarrow \tau^+\tau^-)$.

Recent measurements of $\Delta\Gamma_s$ and $\beta_s^{J/\psi\phi}$ by the CDF and DØ collaborations exclude the SM prediction to 90% C.L.. We illustrate with the example of the scalar leptoquark model that $\Delta\Gamma_s$ as large as 0.4 ps^{-1} may be achieved, and values in the $(\Delta\Gamma_s, \beta_s^{J/\psi\phi})$ parameter space close to the best fit from these measurements can be obtained. Indeed, if future experiments decrease the errors on these quantities while keeping the best fit values at their current positions, only models belonging to this class will be able to explain the deviation from the SM.

The explanation of anomalous like-sign dimuon charge

asymmetry recently observed at $D\bar{O}$ is also facilitated by this class of models, since these models give rise to large $\Delta\Gamma_s$ as well as large β_s^{sl} simultaneously. We point out that these models in general imply that $\beta_s^{\text{sl}} \neq \beta_s^{J/\psi\phi}$, so one has to be careful when including NP in the analysis. Also, note that this mechanism affects A_{sl}^b through the modification of $\Delta\Gamma_s$ and ϕ_s , without the need of an explicit $b \rightarrow s\mu^+\mu^-$ coupling. This is a common feature of all models which have an absorptive part in the $B_s-\bar{B}_s$ mixing diagram.

In order to confirm the compatibility of such models with the data, one needs further NLO calculations of the predictions of these models, as well as a better measurement of $B_s \rightarrow \tau^+\tau^-$ branching ratio, which will be crucial to constrain the leptoquark couplings. The τ from $B_s \rightarrow \tau^+\tau^-$ may be expected to have enough energy boost at the LHC to be detected. The τ polarization can also be measured: the τ 's coming from leptoquarks are expected to be right handed. In addition, if we have an

$SU(2)_L$ doublet leptoquark $\mathcal{S}_{\frac{1}{2}}$, this will also give rise to the FCNC top decay $t \rightarrow c\tau^+\tau^-$ at the level of 1%, which will be another probe of the new physics of this class.

Acknowledgements

We thank B. Dobrescu and D. Hedin for pointing us to the latest bounds on leptoquark masses, and A. Lenz for his clarification about various β_s phases. A.K. acknowledges CSIR, Government of India, and the DRS programme of UGC, Government of India, for financial support. S.N. is supported in part by MIUR under contract 2008H8F9RA_002 and by the EU's Marie-Curie Research Training Network under contract MRTN-CT-2006-035505 'Tools and Precision Calculations for Physics Discoveries at Colliders'.

-
- [1] For a recent review, see P. Ball and R. Fleischer, Eur. Phys. J. C 48, 413 (2006).
 - [2] C. Amsler *et al.* [Particle Data Group Collaboration], Phys. Lett. B667, 1 (2008), and 2009 partial update for the 2010 edition (URL: <http://pdg.lbl.gov>).
 - [3] V. M. Abazov *et al.* [DØ Collaboration], Phys. Rev. Lett. 97, 021802 (2006); A. Abulencia *et al.* [CDF - Run II Collaboration], Phys. Rev. Lett. 97, 062003 (2006).
 - [4] M. Bona *et al.* [UTfit Collaboration], JHEP 0610 (2006) 081.
 - [5] A. Lenz and U. Nierste, JHEP 0706, 072 (2007); A. Lenz, arXiv:hep-ph/0612176; A. Lenz, Nucl. Phys. Proc. Suppl. 177-178, 81 (2008).
 - [6] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. 100, 161802 (2008); V. M. Abazov *et al.* [DØ Collaboration], Phys. Rev. Lett. 101, 241801 (2008).
 - [7] T. Aaltonen *et al.* [CDF collaboration], CDF public note CDF/PHYS/BOTTOM/CDFR/9787, June, 2009.
 - [8] A.S. Dighe *et al.*, Phys. Lett. B369, 144 (1996).
 - [9] A.S. Dighe, I. Dunietz and R. Fleischer, Eur. Phys. J. C 6, 647 (1999).
 - [10] E. Barberio *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:0808.1297 [hep-ex] (URL: <http://www.slac.stanford.edu/xorg/hfag>).
 - [11] S. Nandi and U. Nierste, Phys. Rev. D 77, 054010 (2008).
 - [12] Y. Grossman, Phys. Lett. B 380, 99 (1996).
 - [13] A.J. Buras *et al.*, Phys. Lett. B500, 161 (2001).
 - [14] A. Dighe, A. Kundu and S. Nandi, Phys. Rev. D 76, 054005 (2007).
 - [15] V. M. Abazov *et al.* [DØ Collaboration], arXiv:1005.2757 [hep-ex].
 - [16] CDF Collaboration, "Measurement of CP asymmetry in semileptonic B decays", Note 9015, Oct. 2007.
 - [17] L. Randall and S. F. Su, Nucl. Phys. B 540, 37 (1999).
 - [18] J.C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974); H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32, 438 (1974).
 - [19] B. Schrempp and F. Schrempp, Phys. Lett. B153, 101 (1985).
 - [20] A. Dobado, M.J. Herrero and C. Munoz, Phys. Lett. B191, 449 (1987); J.F. Gunion and E. Ma, Phys. Lett. B195, 257 (1987).
 - [21] S. Davidson, D. Bailey, and B.A. Campbell, Zeit. Phys. C 61, 613 (1994); M. Leurer, Phys. Rev. D 49, 333 (1994); Phys. Rev. D 50, 536 (1994).
 - [22] J. Blumlein, E. Boos and A. Kryukov, Zeit. Phys. C 76, 137 (1997); B. Dion *et al.*, Eur. Phys. J. C 2, 497 (1998); V.A. Mitsou *et al.*, Czech. J. Phys. 55, B659 (2005); M. Kramer *et al.*, Phys. Rev. D 71, 057503 (2005); A. Belyaev *et al.*, J. High Energy Physics 0509, 005 (2005); P. Fileviez Perez *et al.*, Nucl. Phys. B819, 139 (2009).
 - [23] V. M. Abazov *et al.* [DØ Collaboration], arXiv:1005.2222 [hep-ex].
 - [24] V. M. Abazov *et al.* [DØ Collaboration], Phys. Rev. Lett. 101, 241802 (2008).
 - [25] Y. Grossman, Z. Ligeti and E. Nardi, Phys. Rev. D 55, 2768 (1997).
 - [26] J. Hagelin, Nucl. Phys. B193, 123 (1981); A. Ali and C. Jarlskog, Phys. Lett. B144, 266 (1984); L.-L. Chau and W.-Y. Keung, Phys. Rev. D 29, 592 (1984).
 - [27] E. Franco, M. Lusignoli and A. Pugliese, Nucl. Phys. B194, 403 (1982); L. L. Chau, Phys. Rept. 95 (1983) 1; A.J. Buras, W. Slominski, and H. Steger, Nucl. Phys. B245, 369 (1984); V. A. Khoze *et al.*, Sov. J. Nucl. Phys. 46, 112 (1987) [Yad. Fiz. 46, 181 (1987)]; A. Datta, E.A. Paschos and U. Turke, Phys. Lett. B196, 382 (1987); A. Datta, E.A. Paschos and Y.L. Wu, Nucl. Phys. B311, 35 (1988).
 - [28] A. Badin, F. Gabbiani and A. A. Petrov, Phys. Lett. B653, 230 (2007).
 - [29] M. Beneke, G. Buchalla and I. Dunietz, Phys. Rev. D 54, 4419 (1996); M. Beneke *et al.*, Phys. Lett. B 459, 631 (1999); M. Beneke, G. Buchalla, A. Lenz and U. Nierste, Phys. Lett. B 576, 173 (2003); M. Ciuchini *et al.*, J. High Energy Physics 0308, 031 (2003).